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Performance Analysis for High-Speed Railway Communication Network using Stochastic Network Calculus

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***Abstract*— High-speed railway (HSR) wireless communication network has won a great development in recent years. However, due to its unique characteristics, such as high speed, fixed mobility track, special traffic, frequent handover and bandwidth constraints, it is quite a challenge to carry out the performance analysis on HSR. In this paper, we derive the backlog and delay bounds for HSR communication network by using stochastic network calculus (SNC) with moment generating functions (MGFs). SNC is a highly useful tool in packet switched network performance analysis since 1990s. Different from the previous studies about SNC which mostly concentrate on general low-speed, traditional public communication network, we take the varying small-scale fading and large-scale fading into consideration by means of a novel multi-dimension finite-state Markov channel (FSMC) model. We elaborate the differences in packet-level channel model, traffic model of train control information and performance metrics in HSR communication network. Particularly, the backlog and delay bounds of HSR with different packet arrival rates and violation probabilities are derived when train travels from the cell center to the cell edge. What is more, the numerical results can help to provide a guideline for designing the proper violation probabilities and arrival rates to different types of traffic in HSR communication network.**

***Index Terms*—High-speed railway, stochastic network calculus, finite-state Markov channel, backlog bound, delay bound.**

I. Introduction

In recent years, to satisfy the large amounts of data requirements and strengthen railway operation safety guarantees, Long Term Evolution for Railway (LTE-R) is put forward to be the next generation wireless communication for high-speed railway (HSR). It succeeds the key technologies of LTE, such as employing all-IP packet switching, which means all the original and novel traffic will be transmitted through packet switching pattern. Besides, the speed of HSR is faster and faster, generally reaching 200km/h-350km/h. Accordingly, to guarantee the safety and reliability of the train, the precise system performance analysis should be carried out before the operation of HSR.

Consequently, an advanced analysis tool is in need to follow the new technological developments. Network Calculus (NC) is an elegant theory tool of network performance analysis, firstly proposed in 1991 by Cruz [1], [2]. It is quite different with queueing theory which is applied in circuit-switched telecommunication networks. Dealing with performance guarantees in modern packet-switched Internet networks, NC has played an important role in the development of QoS guarantee calculus in packet network [13]. Afterwards, NC has evolved into two branches-Deterministic Network Calculus (DNC) and Stochastic Network Calculus (SNC). There are quite a lot of studies on DNC, which mainly concern the worst performance bound analysis. In reality, however, the probability of the worst case is quite small, leading to the over-optimization of the network resources, where most of the traffic can tolerate some service quality loss, especially considering aggregate traffic [3]. To solve this problem, it has motivated the development of SNC. SNC is the probabilistic version with statistical bounds, allowing a defined probability at most to violate. As a result, it can acquire the stochastic service quality guarantee of the system, with better statistical multiplexing gain and resource utilization.

Over the course of past 20 years, SNC has become a significant direction in NC field, creating a quantity of studies on it. [4] proposed the maximum-(virtual)-backlog-centric (m.b.c) stochastic arrival curve and the stochastic service curve, and proved all the five basic properties (Superposition Property, Concatenation Property, Output Characterization, Leftover Service and Service Guarantees) were satisfied in SNC. These five properties make SNC more and more challenging. Nevertheless, SNC is quite difficult to apply the concatenation property. In the same year, a kind of SNC based on moment generating functions (MGFs) was further developed in [3], which was first proposed in [5]. Under the idea of MGFs, arrival curve and service curve can be equivalent to the MGFs of arrival process and service process. In [6], a service curve model for Gilbert-Elliott channels and the delay and backlog bounds in fading channel were presented by using SNC with MGFs. Also, [7] provided a stochastic service curve model for the Rayleigh fading channel. As the concatenation property shows, considering a set of network nodes as a whole [4], [6], [8], SNC can solve the delay and backlog bounds of multi-hop network, for example [9], [10]. In recent work [11], the author investigated the stochastic delay bound and backlog bound provided by finite-state Markov channel (FSMC) model, where single-user case and multi-user case with different channel sharing methods were considered. Until now, SNC has achieved success in Internet QoS performance analysis, and has been applied to many performance fields, such as wireless sensor network, etc.

However, to the best of our knowledge, there is no literature to analyze the performance of HSR communication system using SNC with MGFs. All of the existing researches are about general low-speed scenario without considering the large-scale variation of average received signal to noise ratio (SNR), and the fast fading is usually described as Rayleigh fading channel model without taking the line of sight (LoS) into account. Besides, the utilized packet-level channel models are mostly on-off two-state Markov chains. These assumptions are not suitable for HSR mobile scenario. Hence, there is not only crucial academic value but also urgent real meaning to promote the research about HSR.

In this paper, we firstly introduce SNC into HSR communication network performance analysis. At the beginning, we fully analyze the unique features of HSR, such as high speed, fixed mobility track, customized train control traffic and specific performance metrics. To achieve the precise performance bounds in HSR, we should take all of those factors into consideration. Therefore, it brings a big challenge to the performance analysis of HSR. By applying a multi-dimension FSMC model [12], we can derive the MGFs of high-speed wireless channel. Moreover, on the assumption of a simplified traffic model, the backlog and delay upper bounds are received. To describe the steady state probabilities and performance bounds in different intervals between two base stations (BSs), the numerical analysis and results are presented.

The rest of this paper is organized as follows. Section II presents a description of the system model, including the background knowledge of SNC and the analysis in HSR communication network. The delay and backlog bounds of HSR are analyzed in Section III. In Section IV, the numerical results are discussed. At last, we give a conclusion about this paper in Section V.

II. System Model

A. Basics of Stochastic Network Calculus

In this section, we show a brief overview on stochastic network calculus with moment generating functions, which are mostly found from the corresponding literatures [3], [4], [8], [13].

Similar to other system theories applied to computer network, SNC divides the queueing system into arrival process, service process and departure process, where the first two processes can be modeled as traffic model and server model. SNC includes two basic tools-arrival curve and service curve. Arrival curve is used to bind the behavior of traffic into the network nodes, in addition, service curve is an abstract expression of schedular describing service guarantees supported by network nodes, as shown in Fig. 1.

The essential idea of SNC is adopting min-plus algebra to transform the complex nonlinear system into tractable linear system [12]. Min-plus mainly turns addition into minimum, as well as, multiplication into addition.

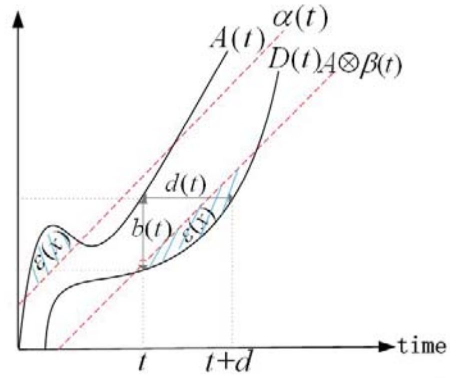

Fig. 1. A basic description of stochastic network calculus.

Let $A(0,t)$, $D(0,t)$ and $S(0,t)$, real-cumulative functions, denote arrival process, departure process and service process in the interval (0,t] respectively. In detail, $A(0,t)$ describes the amount of traffic arriving at the channel, $D(0,t)$ describes the amount of traffic departing from the channel, and $S(0,t)$ describes the amount of service provided by the channel. All of them are wide-sense non-negative non-decreasing, and we assume $t \geqslant 0$, by convention, we have $A(0)$=$D(0)$=$S(0)$=0. When $0 \leqslant s \leqslant t$, we denote $A(s,t) = A(0,t) - A(0,s)$, $D(s,t) = D(0,t) - D(0,s)$, $S(s,t) = S(0,t) - S(0,s)$. In [4], it is proved that better and tighter bounds are achieved when flows and servers are independent. Hence, in this paper, we suppose the arrival process and service process are statistically independent stationary random processes.

Definition 1 (Dynamic Server). Consider a lossless system, it is called a dynamic server if for all $t \geqslant 0$ that

$$D(0,t) \geqslant A \otimes S(0,t). \tag{1}$$

Definition 2 (Backlog and Delay). The backlog of the traffic in the system at time t is

$$b(t) = A(0,t) - D(0,t). \tag{2}$$

The delay at time t is

$$d(t) = \inf\{d \geqslant 0 : A(t) \leqslant D(t+d)\}. \tag{3}$$

Generally, we assume $\theta \geqslant 0$, and the moment generating functions of $A(0,t)$ and $S(0,t)$ are defined as follows

$$\mathrm{M}_A(\theta,t) = \mathrm{E}e^{\theta A(0,t)}, \tag{4}$$

$$\mathrm{M}_S(\theta,t) = \mathrm{E}e^{\theta S(0,t)}, \tag{5}$$

where E describes the expectation of the random variable. We also use the notation

$$\overline{\mathrm{M}}_S(\theta,t) = \mathrm{E}e^{-\theta S(0,t)}. \tag{6}$$

B. High Speed Railway Communication Network

Due to the unique characteristics in HSR, traffic model, performance metrics and channel model are not alike as public communication network. In addition, the allocated bandwidth is also limited. All of the above bring a big challenge to the wireless network performance evaluation.

1) Traffic Model: The anticipated train control traffic in LTE-R system will contain railway safety guarantee traffic, railway transportation management traffic and passenger information service traffic. Therefore, the traffic types, traffic characteristics and user behavior of HSR are somewhat different from public network traffic. For this reason, we need to measure the network traffic of train control information. Afterwards, by means of statistical analysis, theoretical analysis and simulation, the accurate and appropriate traffic model aiming at high-speed scenario can be established.

On the other hand, the QoS metrics system of voice traffic in circuit domain and data traffic in packet domain in GSM-R system have already existed according to RAMS requirements. In addition, towards different traffic types, it has corresponding performance metrics, such as connection establishment delay, connection establishment error ratio, data transmission interference, error-free period, transfer delay of user data frame, connection loss rate and GSM-R network registration delay. In the next generation HSR mobile communication system, it should meet both the safety guarantee of railway train control information and customer satisfaction of non-train control service. Therefore, it is also highly necessary to make the appropriate performance metrics in LTE-R system.

2) Channel Model: Finite-state Markov channel (FSMC) model, the important packet-level channel model, has been widely studied in many literatures, such as [14]–[16] in recent years. Commonly, the general first-order FSMC model is mostly thought more precise, appropriate and tractable in slow-fading channels than in medium-rate or fast-fading channels [14]. In HSR scenario, fast fading, shadowing effect and path loss are not constants but varying rapidly due to high-speed mobility, which are different from the assumptions of existing FSMC model. Besides, LoS path exists in typical multipath viaduct environment and the averaged received SNR fluctuates periodically when the train travels along the railway [12]. In that case, we must take the varying small-scale fading, large-scale fading and shadowing effect into consideration. Recent work [12] proposed a multi-dimension FSMC model for HSR wireless communication channel. It divides the region between two adjacent BSs into several intervals as shown in Fig. 2. In each interval, the fast-fading channel is modeled as a Rician channel, the shadowing effect is modeled as a Lognormal distributed channel and the propagation model is based on WINNER II D2a sub-scenario channel model. Because the time scale of shadowing effect stays between fast fading and path loss, for simplicity, in this paper, we only take fast fading and path loss into consideration.

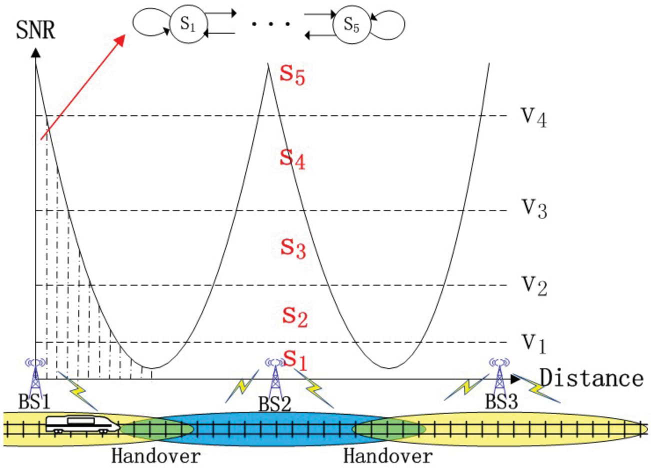

Fig. 2. System model in HSR communication network.

III. HSR Communication Network Performance Analysis

The HSR wireless communication channel and the traffic in HSR can be described as a dynamic server $S(0,t)$ and an arriving process $A(0,t)$, respectively. Taking advantage of Chernoff's theorem [1], we can turn the violation probability when the observed performance exceeds upper bounds into the MGFs of random processes as follows: $P\{X \geqslant x\} = P\{e^{\theta X} \geqslant e^{\theta x}\} \leqslant \varepsilon(x) = e^{-\theta x}\mathrm{M}_X(\theta)$, where X is random variable, x is upper bound, $\varepsilon \in (0,1]$ is violation probability. The observed performances we are interested here are backlog and delay. After substitution and simplification, we can achieve the backlog and delay bounds with MGFs.

Assuming first-come first-served scheduling, $\varepsilon \in (0,1]$ is violation probability, then upper bounds b and d are given by [6]

$$b = \inf_{\theta>0}[\frac{1}{\theta}(\ln\sum_{s=0}^{\infty}\mathrm{M}_A(\theta,s)\overline{\mathrm{M}}_S(\theta,s) - \ln\varepsilon)], \quad (7)$$

$$d = \inf_{\theta>0}\{\inf[\tau : \frac{1}{\theta}(\ln\sum_{s=\tau}^{\infty}\mathrm{M}_A(\theta,s-\tau)\overline{\mathrm{M}}_S(\theta,s) - \ln\varepsilon)) \leqslant 0]\}. \quad (8)$$

We use the received SNR to determine the channel state. The received SNR range is divided into m non-overlapping intervals, such as $[0,v_1)$,$[v_1,v_2)$,...,$[v_{m-1},\infty)$ corresponding to s_1,s_2,...,s_m, and the channel transmission rates of corresponding channel states are r_1,r_2,...,r_m, where v_k denotes the SNR threshold, s_k denotes the kth state, and r_k is the transmission rate of s_k, $k \in \{1,2,\ldots,m\}$. To maximum the bandwidth efficiency and system capacity, we adopt adaptive modulation and coding (AMC) technology [17], which can adjust transmission rates according to different states. In this paper, the SNR thresholds and corresponding transmission rates are listed in TABLE I [18].

TABLE I
SNR AND RATE THRESHOLDS

State	Rate	Modulation	SNR Threshold
1	1	BPSK	6.3281
2	2	QPSK	9.3945
3	3	8-QAM	13.9470
4	4	16-QAM	16.0938
5	5	32-QAM	20.1103

We utilize the multi-dimension FSMC model in [12] as the packet-level channel model in HSR communication network. There are I intervals between BS1 and BS2. In interval i ($i = 1, 2, \ldots, I$), the steady state probability of $s_k (k = 1, 2, \ldots, m)$ is obtained by integrating f_{Γ^i} over the region, as

$$\pi_k^i = \int_{v_k}^{v_{k+1}} f_{\Gamma^i}(\gamma)\, d\gamma = F_{\Gamma^i}(v_{k+1}) - F_{\Gamma^i}(v_k). \tag{9}$$

where f_{Γ^i} is the probability density function (PDF) of SNR, $F_{\Gamma^i}(v_k)$ is the cumulative distribution function (CDF) of SNR in interval i.

The state transition probability can be approximately calculated by level crossing rate (LCR) method. LCR, denoted by $\Lambda(v_k)$, describes the frequency of channel fading [14]. The fast fading is modeled as Rician model, so the LCR of Rician channel can be achieved as [12],

$$\Lambda(v_k) = \sqrt{2\pi(1+k)}\sqrt{\frac{v_k}{\bar{\gamma}_i}} f_d \exp(-K - (1+K)\frac{v_k}{\bar{\gamma}_i})$$

$$I_0(2\sqrt{\frac{v_k}{\bar{\gamma}_i}}\sqrt{K(1+K)}) \tag{10}$$

where $\bar{\gamma}_i$ denotes the average received SNR in interval i, f_d denotes the maximum Doppler frequency shift, and K is the Rice factor.

The state transition probability in interval i is represented by

$$p_{k,k-1}^i \approx \frac{\Lambda(v_k)T_s}{\pi_k^i}, k = 1, 2, \ldots, m-1, \tag{11}$$

$$p_{k,k+1}^i \approx \frac{\Lambda(v_{k+1})T_s}{\pi_k^i}, k = 1, 2, \ldots, m-1, \tag{12}$$

Besides,

$$p_{k,k}^i = \begin{cases} 1 - p_{k,k+1}^i - p_{k,k-1}^i & k = 2, 3, \ldots, m-1, \\ 1 - p_{1,2}^i & k = 1, \\ 1 - p_{m,m-1}^i & k = m. \end{cases} \tag{13}$$

Then we can derive the steady state distribution vector $\boldsymbol{\pi}^i$ and the state transition matrix $\mathbf{Q}^i$ in interval i ($i = 1, 2, \ldots, I$)

$$\boldsymbol{\pi}^i = (\pi_1^i, \pi_2^i, \ldots, \pi_m^i) \tag{14}$$

TABLE II
SYSTEM SIMULATION PARAMETERS

Parameter	Value	Parameter	Value
R	2km	I	70
v	360km/h	K	6dB
h_B	30m	h_m	2.5m

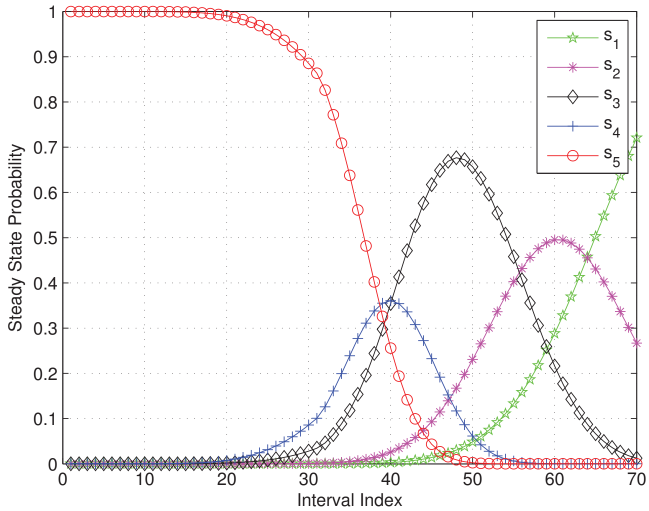

Fig. 3. Steady state probabilities for HSR scenario.

$$\mathbf{Q}^i = \begin{bmatrix} p_{1,1}^i & p_{1,2}^i & \cdots & p_{1,m}^i \\ p_{2,1}^i & p_{2,2}^i & \cdots & p_{2,m}^i \\ \cdots & \cdots & \cdots & \cdots \\ p_{m,1}^i & p_{m,2}^i & \cdots & p_{m,m}^i \end{bmatrix} \tag{15}$$

Then, the MGFs of the service process in the ith interval are derived as

$$\mathrm{M}_{S^i}(\theta, t) = \boldsymbol{\pi}^i(\mathbf{R}(\theta)\mathbf{Q}^i)^{t-1}\mathbf{R}(\theta)\mathbf{1}_m, \tag{16}$$

$$\overline{\mathrm{M}}_{S^i}(\theta, t) = \boldsymbol{\pi}^i(\mathbf{R}(-\theta)\mathbf{Q}^i)^{t-1}\mathbf{R}(-\theta)\mathbf{1}_m. \tag{17}$$

where $\mathbf{R}(\theta)$ is the service rate matrix, defined as $\mathbf{R}(\theta) = \mathrm{diag}(e^{\theta r_1}, e^{\theta r_2}, \ldots, e^{\theta r_m})$.

IV. Numerical Results

In this section, the numerical results of backlog and delay bounds in HSR are achieved based on the knowledge presented before. The simulation parameters are shown in TABLE II. Where, R is the cell radius, I is the number of intervals, v is the train speed, h_B and h_m are the heights of BS and MS respectively, K is the Rice factor.

There are many existing traffic models at present, such as periodic source, fluid source, Gaussian source, General on-off source and so on, [19] elaborates the effective bandwidths of them, from which the corresponding MGFs can be achieved. Furthermore, to simplify the analysis, we approximately assume the traffic model as periodic source in [6], for more details see [19].

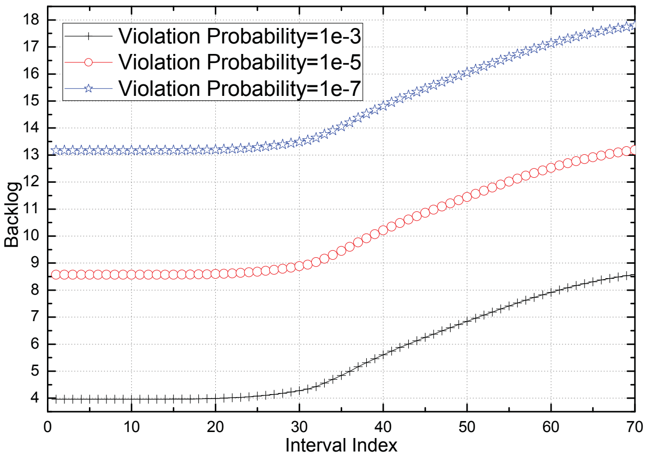

Fig. 4. Backlog bounds with different violation probabilities.

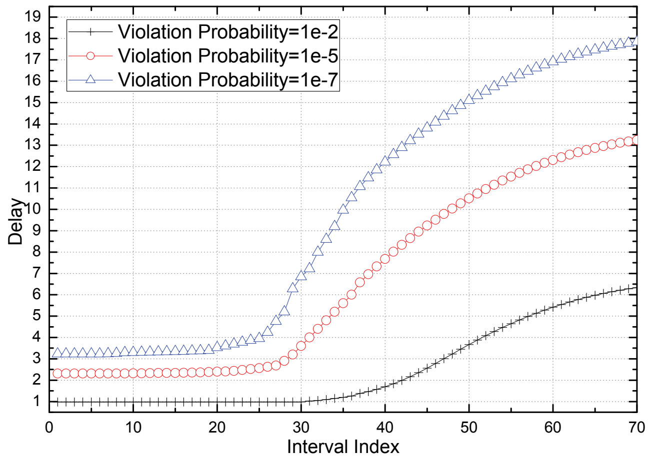

Fig. 6. Delay bounds with different violation probabilities.

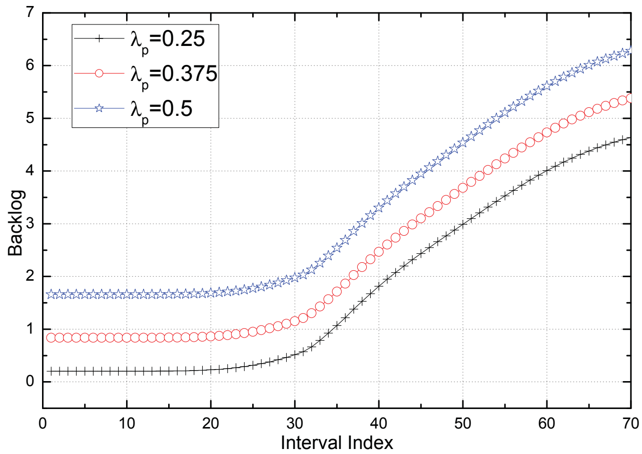

Fig. 5. Backlog bounds with different packet arrival rates.

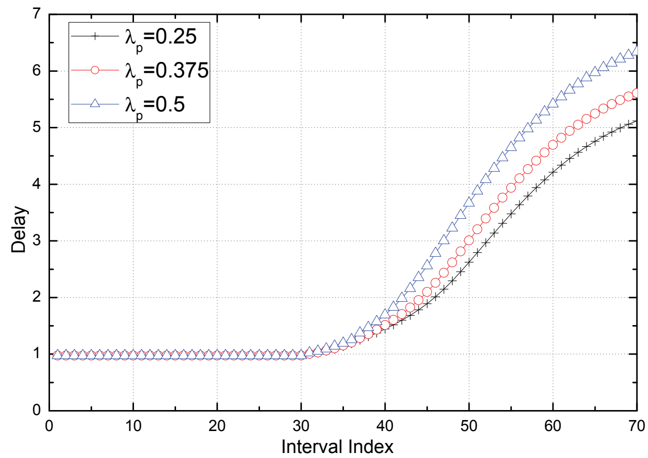

Fig. 7. Delay bounds with different packet arrival rates.

Besides, we assume the train is traveling in the direction from BS1 to BS2, the fast-fading channel is a Rician channel and the propagation model is WINNER II D2a sub-scenario model. We partition the channel states into five levels, the corresponding SNR thresholds and transmission rates in each channel state are listed in TABLE I. For simplicity, we only consider the region from BS1 to its cell edge, referring to interval 0-70, where the length of an interval is 28.571m.

At first, Fig. 3 sketches the variation of steady state probability when train travels from BS1 to the cell edge. When the train is in the interval 0-40, that is less than 1km, the steady state probability of s_1 almost equals to 1, implying the SNR in this region mostly above 20.1103dB. When the train is in the interval far away from BS1, the probabilities of worse channel states rise up. In detail, the averaged received SNR is approximately 13.9470-16.0938dB near interval 50, 9.3945-13.9470dB near interval 60, 6.3281-9.3945dB near the cell edge.

Afterwards, through numerical analysis method elaborated above, the backlog and delay bounds with different violation probabilities $\{10^{-2}, 10^{-3}, 10^{-5}, 10^{-7}\}$ under the same packet arrival rate $\lambda_p = 0.5$ are given in Fig. 4 and Fig. 6. With the decrease of violation probability, the backlog and delay bounds will increase. It is due to the performance bounds will come close to the deterministic worst case performance bounds when the violation probability is near zero. Thus, in reality, we should choose the proper violation probability according to the reliability requirements of different train control information. For example, when considering railway safety guarantee traffic, the violation probability should be lowered to make it foolproof. Besides, it is well known to us that the performance will degrade when train is close to the cell edge. And from the numerical results in Fig. $4-7$, we can see it follows the fact well. Moreover, it is worth noting that the increasing rates of delay in Fig. $6, 7$ are different from backlog in Fig. $4, 5$.

Fig. 5 and Fig. 7 show the backlog and delay bounds with different packet arrival rates $\{0.25, 0.375, 0.5\}$ under the same violation probability 10^{-2}. From the results, we find that the backlog and delay bounds become larger and worse with the increase of packet arrival rate. It's in line with the fact that the channel handling ability is limited. Backlog and delay performance will deteriorate quickly when packet arrival rate exceeds the channel transmission rate. Moreover, according to QoS class identifier (QCI) property, different traffic types have different delay grades according to the corresponding real-time requirements. Thus, the arrival rates of different kinds of traffic should be managed under the upper limits to satisfy the performance bounds.

V. Conclusion

In this paper, the focus is mainly about the application of stochastic network calculus in high speed railway communication network. We elaborate the differences such as traffic model, performance metrics and packet-level channel model in HSR performance analysis using SNC with MGFs. In detail, we realize the backlog and delay bounds taking high-speed fast fading into consideration, using a novel multi-dimension FSMC model to replace the general FSMC model. Numerical results are presented to demonstrate the variation of performance bounds in HSR with different violation probabilities and packet arrival rates. The numerical results are also helpful to provide a guideline for designing the proper violation probabilities and arrival rates to different types of traffic in HSR communication network. Further work will include bringing in the handover mechanism based on the study of backlog and delay bounds.

Acknowledgment

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References

[1] R. Cruz, "A calculus for network delay. I. network elements in isolation," *IEEE Transactions on Information Theory*, vol. 37, no. 1, pp. 114–131, 1991.

[2] ——, "A calculus for network delay. II. network analysis," *IEEE Transactions on Information Theory*, vol. 37, no. 1, pp. 132–141, 1991.

[3] M. Fidler, "An end-to-end probabilistic network calculus with moment generating functions," in *14th IEEE International Workshop on Quality of Service*, 2006, pp. 261–270.

[4] Y. Jiang, "A basic stochastic network calculus," *Proceeding of ACM SIGCOMM*, pp. 123–134, 2006.

[5] C. S. Chang, "Performance guarantees in communication networks," *Springer-Verlag*, 2000.

[6] M. Fidler, "Wlc15-2: A network calculus approach to probabilistic quality of service analysis of fading channels," in *Global Telecommunications Conference*, 2006, pp. 1–6.

[7] H. She, Z. Lu, A. Jantsch, D. Zhou, and L.-R. Zheng, "Modeling and analysis of Rayleigh fading channels using stochastic network calculus," in *Wireless Communications and Networking Conference (WCNC)*, 2011, pp. 1056–1061.

[8] F. Ciucu, A. Burchard, and J. Liebeherr, "A network service curve approach for the stochastic analysis of networks," in *SIGMETRICS05*, Banff, Alberta, Canada, 2005.

[9] K. Zheng, L. Lei, Y. Wang, Y. Lin, and W. Wang, "Quality-of-service performance bounds in wireless multi-hop relaying networks," *Communications, IET*, vol. 5, no. 1, pp. 71–78, 2011.

[10] H. Al-Zubaidy, J. Liebeherr, and A. Burchard, "A network calculus approach for the analysis of multi-hop fading channels," *arXiv:1207.6630*, 2012.

[11] K. Zheng, F. Liu, L. Lei, C. Lin, and Y. Jiang, "Stochastic performance analysis of a wireless finite-state markov channel," *IEEE Transactions on Wireless Communications*, vol. 12, no. 2, pp. 782–793, 2013.

[12] S. Lin, Z. Zhong, L. Cai, and Y. Luo, "Finite state markov modelling for high speed railway wireless communication channel," in *Global Communications Conference (GLOBECOM)*, 2012, pp. 5421–5426.

[13] Y. Jiang, "Stochastic network calculus for performance analysis of Internet networks - an overview and outlook," in *2012 International Conference on Computing, Networking and Communications (ICNC)*, 2012, pp. 638–644.

[14] P. Sadeghi, R. Kennedy, P. Rapajic, and R. Shams, "Finite-state markov modeling of fading channels - a survey of principles and applications," *Signal Processing Magazine, IEEE*, vol. 25, no. 5, pp. 57–80, 2008.

[15] Q. Zhang and S. Kassam, "Finite-state markov model for Rayleigh fading channels," *IEEE Transactions on Communications*, vol. 47, no. 11, pp. 1688–1692, 1999.

[16] C. Pimentel, T. Falk, and L. Lisboa, "Finite-state markov modeling of correlated Rician-fading channels," *IEEE Transactions on Vehicular Technology*, vol. 53, no. 5, pp. 1491–1501, 2004.

[17] A. Goldsmith and S.-G. Chua, "Adaptive coded modulation for fading channels," *IEEE Transactions on Communications*, vol. 46, no. 5, pp. 595–602, 1998.

[18] Q. Liu, S. Zhou, and G. Giannakis, "Queuing with adaptive modulation and coding over wireless links: cross-layer analysis and design," *IEEE Transactions on Wireless Communications*, vol. 4, no. 3, pp. 1142–1153, 2005.

[19] F. P. Kelly, "Notes on effective bandwidths," *Number 4 in Royal statistical society lecture notes*, pp. 141–168, 1996.